2 Carbon Losses and Sequestration with Land Use Change in the Humid Tropics

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The role of tropical forests in the global carbon (C) cycle has been debated over the past 20 years, as several estimates of the flux of carbon dioxide (CO_2) from tropical deforestation have been proposed (Houghton et al. 1987; Detwiler and Hall 1988; Brown et al. 1993). Current estimates indicate that land use change in the tropics released 1.7 (0.6–2.5) Gt C/yr, compared with 5.4 ± 0.3 Gt C/yr from fossil fuel emissions (IPCC 2001). This flux has been attributed primarily to deforestation in the tropical zone, with Asia and Latin America accounting for more than 80 percent of the flux (Houghton 1997). However, a recent analysis of the net carbon flux from the Brazilian Amazon suggests that carbon sources created by deforestation are offset by carbon sinks from the undisturbed forest and regrowing secondary vegetation (Houghton et al. 2000). As noted by DeFries et al. (1999), reducing the uncertainty of estimates of CO_2 emissions caused by land use change is key to balancing the global carbon budget. Much of the uncertainty in the values of CO_2 flux from the tropics is a result of inadequate estimates for rates of different land use transitions, the biomass of the vegetation that is cleared, the rates of regrowth, and levels of biomass recovery of the subsequent land use systems. In particular there is little information on the carbon stored and the potential to sequester carbon in many of the land use systems of the humid tropics other than for continuous cropping and pasture systems, both of which have low carbon storage potential. However, there is significant tree cover on deforested, agricultural, and abandoned land in the rainfed, or humid, tropics (Fearnside and Guimaraes 1996; Houghton et al. 2000; Silver et al. 2000; Wood et al. 2000) that could provide a potentially large sink for carbon.

One of the primary objectives of the Alternatives to Slash and Burn (ASB) program was to improve information on the carbon stored in the biomass of the vegetation and soils during the various stages of the land use systems established after deforestation in the humid tropics. Changes in carbon stocks associated with the different land use systems combined with details on the time course of these changes during the land use rotation are necessary to estimate the net carbon losses and sequestration potential associated with these different land use conversions.

METHODS

Field Sampling

Above-ground (live trees and understory, dead vegetation, litter layer) and below-ground (roots and soil to 20-cm depth) carbon stocks were measured in forests or other land uses established after slash-and-burn clearing in the benchmark sites in Brazil (Pedro Peixoto and Theobroma), Cameroon (Yaoundé, M'Balmayo, and Ebolowa), and Indonesia (Lampung and Jambi). The land uses sampled at each site together made up a time course, or chronosequence, of land use change. In this type of sampling, called type II studies by Sanchez et al. (1985), the time courses of changes in carbon stocks for different land use scenarios are reconstructed by sampling areas of known but different ages. The preferred sampling method, a type I study, in which the changes in carbon stocks are followed in a single plot through time, is impractical because of the long-term nature of these studies. In type II studies, in which space substitutes for time, care must be taken to sample areas in a chronosequence that have similar soil texture; if not, then differences in carbon stocks that are attributed to land use change might actually be a result of differences in site characteristics that affect carbon storage (Sanchez et al. 1985).

At each location in the benchmark sites, one or two land use chronosequences were sampled. Each chronosequence included the meta–land use systems (chapter 1, this volume) appropriate for each benchmark site. Natural or selectively logged forests served as reference points for baseline data on initial carbon stocks for each chronosequence. The land use sequence was then represented by areas that had recently been slashed, burned, and cropped combined with areas that included various stages of the crop and fallow cycles; various ages of lands subsequently planted to pastures, agroforests, or tree plantations; or stages of cropland and pasture degradation. The management practices, age, and time course, including rotation time of each land use system sampled, were obtained by interviewing the farmers. The land use systems that were evaluated for carbon stocks in each of the benchmark sites are summarized in table 2.1.

Above-ground and below-ground carbon stocks were measured for each land use within the chronosequences according to standardized methods described in Woomer and Palm (1998) and Woomer et al. (2000). Briefly, tree biomass was determined by measuring diameter at breast height (dbh) for all trees with dbh greater than 2.5 cm in five 4- by 25-m quadrats. Diameter was converted to tree biomass by use of the allometric equations for tropical moist forest trees in Brown et al. (1989) or FAO (1997).

Understory biomass was determined by destructively harvesting and drying all vegetation less than 2.5 cm dbh within two 1-m^2 quadrats placed in each tree quadrat. The biomass of the litter layer was determined by removing all surface litter from a 0.5- by 0.5-m quadrat placed in each understory plot. Roots were excavated and soil carbon assessed in a minimum of four 0.2- by 0.2-m quadrats, for the 0- to 0.2-m and 0.2- to 0.5-m soil depths, for each land use per chronosequence. Vegetation, root, and litter biomass were all converted to carbon multiplying by a factor of 0.45. As discussed later, root data were ignored because of their variability.

Calculating Time-Averaged Above-Ground Carbon Stocks and Net Carbon Loss or Sequestration

The carbon stocks of the different land use systems at the ASB sites are presented in Kotto-Same et al. (1997), Fujisaka et al. (1998), and Tomich et al. (1998) and summarized in Woomer et al. (2000). In this chapter, that information was used to calculate the above-ground time-averaged carbon for the different land use systems. The carbon loss or sequestration potential of a land use system is determined not by the maximum carbon stock of the system or the stocks at any one point in time but, rather, by the average carbon stored in that land use system during its rotation time

Table 2.1 Details of the Major Components and Management of the Different Land Use Systems Evaluated for Above-Ground Time-Averaged Carbon for the Different ASB Benchmark Areas

Brazil
Pastures: both extensive and intensive (grass–legume mixtures)
Simple agroforests (single tree crop systems): monoculture coffee plantations (1000 plants/ha), assuming a 7-yr establishment phase plus 5 more years of production for a total rotation time of 12 yr
Simple agroforestry systems (includes three systems: coffee [*Coffea canephora* Pierre ex Froehner] + rubber [*Hevea brasiliensis* (Willd. ex A. Juss.) Muell.-Arg.], coffee + bandarra (*Schizolobium amazonicum* Huber ex Ducke); and cupuaçú [*Theobroma grandiflorum* (Willd. ex Spreng.) Schum] + pupunha (*Bactris gasipaes* Kunth) + castanha [*Bertholletia excelsa* Humb. & Bonpl.]), with an establishment phase of 12 yr and rotation time of 20 yr
Crop–short fallow systems: annual crop–fallow cycles with 3 yr of cropping and 5 yr of natural bush fallow
Crop–short improved fallow systems: annual crop–improved tree fallow with inga (*Inga edulis* Mart.) or senna (*Senna reticulata* [Willd.] H. Irwin and Barneby) cycles with 3 yr of cropping and 5 yr of fallow
Cameroon
*Crop–*Chromolaena *fallow systems:* 2 yr of annual cropping followed by 4 yr of *Chromolaena odorata* (L.) R.M. King and H. Robinson fallow
Crop–short fallow system: 2 yr of cropping followed by 9 yr of secondary forest fallow
Crop–long fallow system: 2 yr of cropping followed by 23 yr of secondary forest fallow
Complex agroforests: 2 yr of cropping followed by establishment of *Theobroma cacao* (jungle cacao) with a 25-yr establishment phase and 40-yr rotation
Complex agroforests: a permanent, nonrotational cacao system established through gap and understory plantings of cacao
S*imple agroforests (single tree crop system):* 1 yr of cropping followed by establishment of an oil palm plantation with 146 trees/ha with a 7-yr establishment phase and a 25-yr rotation
Indonesia
Complex agroforests: 2 yr of annual cropping followed by establishment of a rubber plantation (jungle rubber) with a 25-yr establishment phase and 30-yr rotation time
Complex agroforests: a nonrotational, permanent rubber agroforestry system established through understory and gap plantings
Simple agroforests (intensive tree crop systems): establishment of an industrial oil palm plantation with 120 trees/ha and an establishment phase of 7 yr and rotation time of 25 yr
Simple agroforests (single tree crop system): establishment of an industrial timber plantation of a single fast-growing tree (*Paraserianthes falcataria, Eucalyptus* sp., *Acacia mangium*) with a rotation time of 8 yr
Crop–fallow rotation: 7 yr of cassava followed by 3 yr of *Imperata cylindrica* (L.) Beauv grassland

(ICRAF 1996). This quantity is referred to here as the time-averaged carbon stock and is similar to the average carbon storage method described in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Land Use, Land-Use Change and Forestry (Watson et al. 2000). The time-averaged carbon takes into account the dynamics of systems that include tree regrowth and harvesting and allows the comparison of land use systems that have different tree growth and harvesting rotation times and patterns.

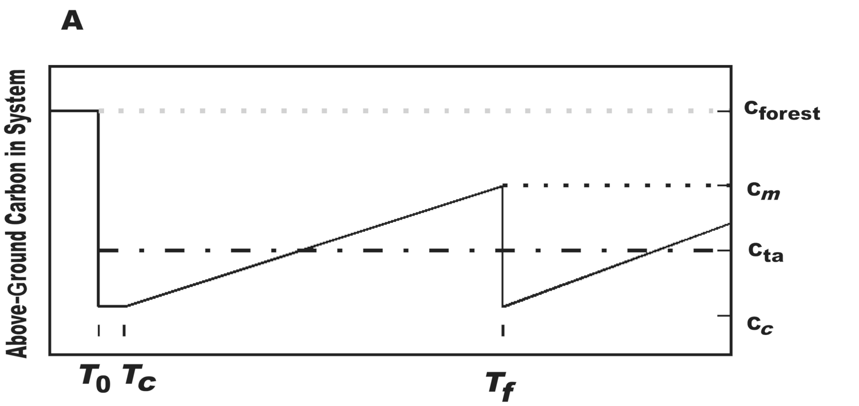
The time-averaged carbon stock depends on the carbon accumulation rates, the maximum and minimum carbon stored in the system during a full rotation, the time it takes to reach maximum carbon, and the rotation time of the system (figure 2.1). Carbon accumulation rates (I_c), in tons of carbon per hectare per year, for above-ground vegetation regrowth were calculated as the carbon stock value of the sampled vegetation (C*s*) divided by the age (T_s) of the vegetation (ICRAF 1996). Average carbon accumulation rates were obtained for each land use system in each country from the individual rates for the replicate chronosequences. It is assumed that the carbon increase rates (I_c) are linear throughout the time period of vegetation regrowth after clearing (T_f). This appears to hold at least for the first 20 years (Brown and Lugo 1990; Fearnside and Guimaraes 1996). The maximum carbon stored in fallows (C*m*) at the time of clearing (T_f) is calculated as $Cm = I_c \times T_f$. The time-averaged carbon stock for a crop–fallow system that has negligible carbon stored in a short cropping phase is essentially the carbon stored in the fallow vegetation at the time of reclearing (C*m*) divided by 2, or the carbon accumulation rate (I_c) times the years of fallow (T_f) divided by 2 (figure 2.1a). For tree crop plantations or some agroforestry systems, however, the maximum carbon stock (C_{max}) may be reached at a time (T_{max}) before the end of the rotation (T_r). As an example, a coffee (*Coffea* spp.) plantation may reach the maximum carbon stock in 7 years (establishment phase), but production continues for an additional 5 years (production phase), giving a rotation time (T_r) of 12 years, at which time the plantation is cut and reestablished. The time-averaged carbon stock for such land use systems is determined as the weighted average of the time-averaged carbon stocks for the different phases of the rotation (figure 2.1b).

Details of the sites sampled, including location, land use categories, and age since clearing and the above-ground and soil carbon stocks used for calculating time-averaged carbon can be found in Palm et al. (2002).

Differences in above-ground carbon stocks between the forest and the above-ground time-averaged carbon of the different land use systems were used to calculate the loss of carbon with the alternative slash-and-burn systems. Likewise the potential for different land use systems to sequester carbon relative to other systems was determined by pairwise comparisons of their time-averaged carbon.

Below-Ground Carbon

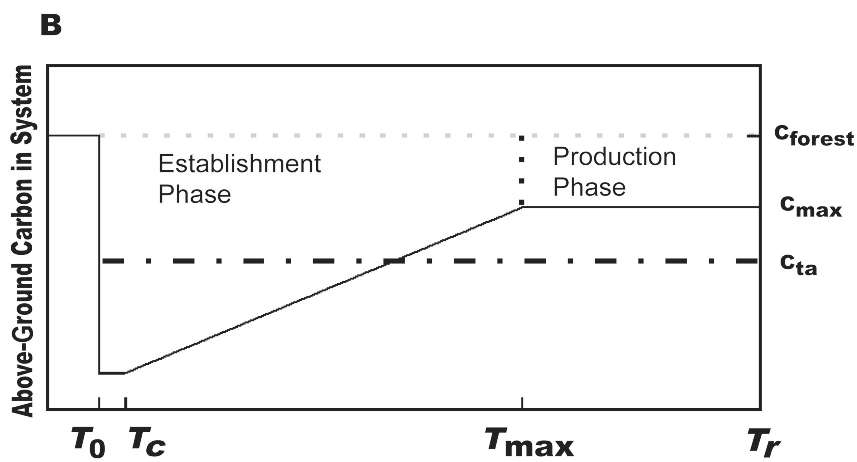
The time-averaged comparison just described was calculated only for the above-ground carbon stocks because the root and soil data were extremely variable and consistent



Carbon accumulation rate = $I_c = (C_m - C_c) / (T_f - T_c)$, or if T_c and C_c are small, then
$I_c = C_m / T_f$

Time-averaged carbon = $(I_c * T_f) / 2$, assuming T_c and C_c are small

C_m = Carbon in fallow at time of clearing
C_c = Carbon in crop, assumed to be negligible
C_{ta} = Time-averaged carbon
T_f = Time (years) in fallow phase
T_c = Time in crop phase, assumed short compared with T_f



Maximum carbon in system = $C_{max} = T_c * T_{max}$

Time-averaged carbon in system = $LUCS_{ta}$

= Weighted mean (C_{ta} establishment and production phases)

C_{ta} establishment phase = $C_{estab} = (I_c * T_{max}) / 2$
C_{ta} production phase = $C_{prod} = C_{max}$
$= [(C_{estab} * T_{max}) + (C_{prod} * [T_r - T_{max}])] / T_r$

T_r = Time of rotation

Figure 2.1 Schematic of the changes in carbon stocks and means for calculating time-averaged carbon stocks after forest clearing and establishment of (**a**) crop–fallow systems and (**b**) tree plantations.

time trends did not emerge that are needed for such calculations. The root data in particular were not useful in making comparisons between land use systems because few significant differences emerged between land use systems.

The soil data were also variable within chronosequences, partially because of textural differences in the soils of the chronosequence sampled at each site, despite attempts to sample similar soils. To account for the variability caused by differences in soil texture within a site, the soil carbon data were normalized using equation 2.1, developed by van Noordwijk et al. (1997) for estimating the soil carbon equilibrium values:

$$\text{Calculated forest soil C} = C_{ref} = \exp(1.333 + 0.00994 \times \%\ \text{clay} + 0.00699 \times \%\ \text{silt} - 0.156 \times \text{pH}_{KCl}). \qquad 2.1$$

The equation was derived with soil carbon data from Sumatra to estimate equilibrium topsoil carbon values for undisturbed forest systems. This C_{ref} value referred to the carbon content of the topsoil as identified in the soil survey data, with a variable depth but generally between 0–5 and 0–10 cm. Another equation developed by van Noordwijk et al. (2000) provides a means for standardizing soil carbon according to variable sampling depths. Equation 2.2, developed from soil data from Jambi Province, Indonesia, shows a relationship between soil carbon content and soil depth in the top 100 cm:

$$\%\text{C} = 8.38\ Z^{-0.58} (R^2 = 0.86), \qquad 2.2$$

where Z is the midpoint of the soil-sampling depth.

By integrating this equation over the sampling depth, we obtain a correction factor:

$$C_{ref}(Z_2) = C_{ref}(Z_1) \times (Z_2/Z_1)^{-0.58}, \qquad 2.3$$

where Z_2 and Z_1 are the midpoint of the sampling depth of a specific sample and the sampling depth, 7 cm, that was used to establish the initial C_{ref} equation, respectively.

The calculated C_{ref} values, corrected for texture and sampling depth, for each land use per site were then compared with the actual carbon measured (C_{act}) to give a relative carbon value (C_{rel}) = C_{act}/C_{ref}. The C_{rel} values indicated the soil carbon in the land use system relative to that expected from a forest system on a similar soil type. The C_{rel} of a forest soil should be 1 if the equation is appropriate for that location and the sampling depth is similar to that used in deriving the equation. The C_{rel} of soils from the different land use systems was then used to estimate the gain or loss of soil carbon relative to that of the forest, with a C_{rel} less than 1 indicating a loss of soil carbon.

An approximation of a time-averaged carbon for the soil over the rotation could then be calculated in a manner similar to that for above-ground carbon. The time-

Table 2.2 Average Above-Ground Carbon Stocks (standard deviation) and Age of the Land Use Systems Sampled at the ASB Benchmark Areas and the Calculated Carbon Accumulation Rates, Maximum Carbon Stock, and Land Use System Time-Averaged Carbon Stock

Meta–Land Use Systems	Country and Specific Land Use		Replicates	Average Carbon Stock of Sample Plots, in t C/ha (*SD*)	Average Age of Sample Plots, in yr (*SD*)	Carbon Accumulation Rate, 100 t C/ha/yr (*SD*)	Age at Maximum Carbon (yr)	Rotation Time of Land Use System (yr)	Maximum Carbon Stock (t C/ha)[a]	Time-Averaged Above-Ground Carbon of Land Use System (t C/ha)[b]
Undisturbed forest	Indonesia		2	306 (99)	>100	NA	NA	NA	306 (207–405)	306 (207–405)
Managed and logged forests	Brazil		4	148 (19)	?	NA	NA	NA	148 (129–149)	148 (129–149)
	Cameroon		5	228 (27)	?	NA	NA	NA	228 (221–255)	228 (221–255)
	Indonesia		4	93.2 (41.3)	?	NA	NA	NA	93.2 (51.9–134)	93.2 (51.9–134)
Crop–fallow rotations	Cameroon	Shifting cultivation, 23-yr fallow	7	131 (37)	18.5 (4.2)	7.26 (2.02)	25	25	167 (120–213)	77.0 (60.2–107)
		Bush fallow, 9.5 yr	5	64.1(18.8)	9.6 (0.9)	6.68 (1.76)	9	11	56.2 (44.3–76.0)	28.1 (22.1–38.1)
		Chromolaena fallow, 4 yr	6	5.78 (2.76)	2	2.89 (1.38)	4	6	11.6 (6.04–17.1)	4.52 (2.6–6.38)

	Brazil	Short fallow, 5 yr	3	15.4 (9.43)	4 (4.0)	3.91 (1.66)	5	8	19.6 (1.2–28.4)	6.86 (4.27–9.61)
		Improved fallow, 5 yr		13.7 (2.51)	2 (0)	6.86 (1.26)	5	8	34.3 (28.0–40.6)	11.5 (9.50–13.4)
Complex agroforests	Cameroon	Cacao	5	88.7 (31.6)	NA	NA	NA	NA	88.7 (57.2–120)	88.7 (57.2–120)
	Indonesia	Rubber	4	89.2 (39.8)	NA	NA	NA	NA	89.2 (49.4–129)	89.2 (49.4–129)
	Cameroon	Cacao	5	88.7 (31.6)	25 (0)	3.55 (1.26)	25	40	88.7 (57.2–120)	61 (40–83)
	Indonesia	Rubber	4	89.2 (39.8)	30	3.57 (1.59)	25	30	89.2 (49.4–129)	46.2 (28.9–75.2)
Simple agroforests and intensive tree crops	Brazil	Coffee monoculture	3	15.0 (2.66)	8 (2.31)	2.14 (0.38)	7	12	15.0	11.0 (8.73–12.5)
	Brazil	Multistrata system	3	70.5 (24.3)	10 (5.2)	7.26 (1.63)	12	20	87.1 (67.6–106.7)	61.2 (47.5–74.7)
	Cameroon	Oil palm	1	42.2	15	6.03	7	25	42.2	36.4
	Indonesia	Pulp trees	2	22.0 (1.91)	2.5 (2.1)	9.29 (3.39)	8	8	74.3 (47.2–101)	37.2 (23.6–50.7)
Grasslands and crops	Brazil	Extensive pastures	4	5.70 (3.43)	11 (1.0)	—	—	8	—	2.85
		Intensive pastures	3	6.04 (1.91)	10 (3.6)	—	—	8	—	3.06
	Indonesia	Cassava–*Imperata*	11	2.05 (0.98)	—	—	—	10	1.97	<2

[a]The range is given in parentheses and was determined by multiplying the age at maximum carbon by ± 1 *SD* of the carbon accumulation rate.

[b]The range was obtained by inserting the range in values for the maximum carbon into the equations for calculating C_{ta}.

averaged calculations for soil carbon are complicated by the pattern of carbon loss and recovery for soil, which shows a time lag relative to that of the recovery of vegetation. There is typically a loss of 10 to 40 percent of the topsoil carbon the first 2 to 5 years after clearing of forests or fallows, with the percentage loss depending on several factors that influence the amount of organic materials returned to the soil. After the loss phase, there is recovery of soil carbon to a level depending on the land use management and rotation times (Szott and Palm 1986; Sommer et al. 2000). For purposes of this study, because there was insufficient detail of the pattern and time course of soil carbon for the different land use systems, the time-averaged topsoil carbon was assumed to simply be that at the end of the rotation indicated in table 2.2. These estimates do not include the temporary loss of soil carbon after fallow clearing and thus would be slight overestimates.

Modeling Carbon Dynamics with Land Use Change

Obtaining more accurate values of carbon stocks, rates of carbon accumulation, and the time course of changes in carbon stocks in tropical land use systems is essential for improving our understanding of the role of tropical land use in the global carbon budget. Yet obtaining this information is extremely time consuming and costly. Once sufficient data have been collected, they can be used to parameterize and validate models that simulate changes in carbon with land use change. Version 4.0 of the CENTURY model is well suited for the purposes of simulating carbon changes with land use in the ASB program because it includes the growth of trees and crops and the complex management practices used in tropical agroecosystems (Metherell et al. 1993). The CENTURY model is a generic plant–soil ecosystem model that has been used to simulate carbon, nitrogen, and phosphorus dynamics of natural and managed ecosystems. Once tested and validated for the different soils, climates, crops and trees of the ASB benchmark sites, the CENTURY model can be used to explore the productivity and carbon losses and sequestration potential of land use alternatives beyond the time frame possible from direct field experimentation and for additional land use systems.

Soil, climate, and land use management data, including clearing and burning, crop type, and sequencing, were used to simulate the pulpwood plantations and cassava–*Imperata* land uses in Indonesia (Sitompul et al. 1996) and conversion from traditional slash-and-burn to tree-based systems in Cameroon (Woomer et al. 2000).

RESULTS AND DISCUSSION

Time-Averaged Above-Ground Carbon

The above-ground carbon stocks in the forest systems differed between sites; the highest, with more than 300 t C/ha, was reported for the natural or undisturbed forests of Indonesia (table 2.2). There were no measurements of natural undisturbed forests at the other sites because they were not found near the study areas. The decreasing above-ground carbon in the managed or logged forests, from a high of 228 t C/ha in Cameroon to a low of 93 t C/ha in Indonesia, reflected varying extraction intensities from a few boles per hectare by the local farmers in Cameroon and Brazil to large-scale extraction by commercial loggers in Indonesia. The values for above-ground carbon in selectively logged forests in Indonesia and Brazil are similar to values reported by FAO (1997). The average value for Brazilian forests fell into the lower estimates used by Houghton et al. (2000) for calculating net CO_2 fluxes from the area. The values for the logged forest of Cameroon and the undisturbed forest of Indonesia were higher than the few values reported by FAO (1997). Increasing the FAO values by 20 to 30 percent to account for understory vegetation, trees with dbh less than 10 cm, and the litter layer (Sandra Brown, pers. comm. 1998) may account for the tendency of higher biomass values obtained with the ASB method.

Slash-and-burn clearing generally is from logged or secondary forests and not undisturbed forests (Fujisaka et al. 1998), so the current carbon losses from slash-and-burn would be lower than if undisturbed forests were cleared. The carbon of logged forests therefore was used as reference point with which other systems were compared. The least intensive of the land use systems, the permanent cacao or rubber agroforests of Cameroon and Indonesia, had maximum and time-averaged carbon stocks of 90 t C/ha, or 40 to 100 percent of the logged forests, respectively. There was a further drop to about 50 t C/ha time-averaged carbon for the rotational, complex cacao and rubber agroforests of Cameroon and Indonesia, representing 22 and 54 percent of the carbon of the logged forests, respectively. The time-averaged carbon of the other rotational, more intensively managed tree-based systems depends on a variety of factors, including planting densities, rotation time, and management factors. The values ranged from a high of 60 t C/ha for the multistrata fruit tree complex agroforests in Brazil to a low of 11 t C/ha in monoculture coffee plantations. The time-averaged carbon of an oil palm plantation in Cameroon was about half that of the cacao complex agroforestry system.

The more intensively managed tree plantation systems do not necessarily have lower time-averaged carbon stocks than the simple agroforestry systems such as the coffee- and oil palm–based ones. As an example, the *Acacia mangium* Willd. or *Paraserianthes falcataria* (L.) I. Nielsen (now called *Falcataria moluccana* [Miq.] Barneby and Grimes) pulp plantations in Indonesia attained a lower maximum carbon stock (74 t C/ha) than complex rubber agroforests (90 t C/ha), but the faster carbon accumulation rates of almost 9 t C/ha/yr compared with 3.5 t C/ha/yr result in similar time-averaged carbon stocks of 40 t C/ha. This emphasizes the importance of regrowth rates and rotation times in time-averaged carbon stocks.

The time-averaged carbon stock of the traditional, long-fallow shifting cultivation still practiced in parts of Cameroon was almost 80 t C/ha. Intensifying the cropping system by shortening the fallow period in Cameroon reduced time-averaged carbon stocks to 28 and 5 t C/ha for systems with 9- and 4-year fallows, respectively. In Brazil, the time-averaged carbon stock of the 5-year natural fallow was 7 t C/ha (5 percent of the forest); the value increased to only 12 t C/ha for improved fallows planted with *Inga* or *Senna* trees but with similar rotation times.

Eventual conversion of deforested land to pastures or continuous cropping systems reduced time-averaged carbon stocks to only about 3 t C/ha, 2 percent that of the logged forest. The average rotation time of a pasture is 8 to 10 years before reestablishment. Intensifying pastures through management or introduction of legumes increased the above-ground carbon by less than 1 C/ha above the traditional pasture systems. Similarly, the cassava–*Imperata* systems in Indonesia had time-averaged carbon stocks of only 2 t C/ha.

Above-ground carbon accumulation rates differed between the meta–land use system categories (table 2.2). Rates were highest, up to 9.3 t C/ha/yr, in the intensive tree crop systems and simple agroforests. The exception to this was coffee monocultures, which had a low accumulation rate of 2.1 t C/ha/yr, a result of the low planting density and intensive pruning. Crop–fallow successions had lower carbon accumulation rates, averaging 3 t C/ha/yr and 7 t C/ha/yr for the short- and long-term natural secondary fallows, respectively. The improved tree fallows in Brazil had a higher carbon accumulation rate of 7 t C/ha/yr, compared with 4 t C/ha/yr for the natural tree fallow of the same rotation time. The chromolaena (*Chromolaena odorata* [L.] R.M. King and H. Robinson) fallow in Cameroon had the lowest accumulation rate, probably because of arrested succession caused by the aggressive cover of the low-biomass chromolaena plants. The complex cacao and rubber agroforestry systems had carbon accumulation rates about half that of the natural fallows, probably from selective slashing and thinning of understory vegetation to reduce competition with the tree cash crops.

There are few data with which to compare the ASB carbon stock and regrowth rates of the fallows, tree crop plantations, and agroforestry systems. Houghton et al. (1993) reported time-averaged carbon values of 50 to 100 t C/ha for agroforestry systems and plantations. These values, in general, are higher than those measured in the ASB systems.

The regrowth rates of the natural fallows estimated for the ASB systems are in the upper range reported in other studies (Uhl et al. 1988; Szott et al. 1994; Fearnside and Guimaraes 1996; Houghton et al. 2000; Silver et al. 2000). The lower regrowth rates are generally found after pasture, rather than crop, abandonment (Uhl et al. 1988; Fearnside and Guimaraes 1996); most of the ASB fallow systems followed cropping, which could partly explain the high regrowth rates.

The ASB dataset allows comparisons of carbon stocks and time-averaged carbon values between meta–land use systems and between sites. Some caution must be taken regarding the precision and accuracy of these estimates. There are several steps in which errors can affect the estimates, including the plot size used for estimating biomass of large trees (Brown et al. 1995), the allometric equations used for estimating tree biomass (Ketterings et al. 2001), an insufficient number of replicates for some of the land use systems, and inaccurate ages of plots and rotation times. The carbon estimates for some of the tree plantations and agroforestry systems were obtained from only two replicates, and the ages at which maximum biomass is attained and rotation times for some of the land use systems were sometimes informed guesses. Further sampling and time course delineation may improve estimates of carbon stocks and time-averaged carbon in some of these tree-based systems.

One of the factors that could introduce the largest errors in carbon stock estimates is the choice of allometric equations used for estimating tree biomass. The equation used for estimating tree biomass for the ASB sites was developed primarily from old age forest stands and for trees with diameters greater than 10 or even 25 cm (Brown et al. 1989). Most of the nonforest, tree-based systems in the ASB site were younger than 20 years, and the majority of trees had diameters less than 25 cm. New allometric equations have since been developed from young secondary forests and fallows in Indonesia (Ketterings et al. 2001) that result in biomass estimates half those obtained from the equation of Brown et al. (1989). The main factors influencing the tree biomass were the height of the trees and the wood density. Several other recent studies have shown a wide range in allometric equations for both primary and secondary forests in the humid tropics of Brazil (Alves et al. 1997; Araújo et al. 1999; Nelson et al. 1999). Such a wide range in carbon estimates for trees stresses the difficulty in assessing vegetation biomass. It does, at least, set an upper (Brown et al. 1989) and lower limit (Ketterings et al. 2001) to these estimates. Further testing and application of the new allometric equations will assist in reducing the uncertainty in carbon stocks and fluxes particularly for the younger fallow and tree-based systems.

Below-Ground Carbon

As mentioned previously, the root biomass data were extremely variable and did not indicate differences between the land use systems. Apparently the excavation method used did not adequately sample large roots, so the values for roots in forests and other tree-based systems were underestimates. These data are not included in the results and will not be discussed. A means for estimating roots through the time course of regrowth of tree-based systems could be to use the root-to-shoot ratios of 0.42 for 5-year regrowth and 0.20 for 20-year secondary regrowth obtained by Fearnside and Guimaraes (1996). Basically this would show that including roots from tree-based systems would magnify the differences in carbon stocks between the land use systems already reported for above-ground vegetation. The case of pasture systems may be quite different, as discussed later in this chapter.

The baseline topsoil (0–20 cm) carbon stocks in the forest systems ranged from 45 to 50 t C/ha in Indonesia and Cameroon and were 35 t C/ha in the Brazil forest sites (table 2.3). Values for the logged forests in Indonesia did not differ from those of the undisturbed forest sites. The baseline values for the ASB sites are on the low end compared with the range of 46 to 69 t C/ha reported by Detwiler (1986), assuming that 45 percent of the carbon in a 1-m profile reported in his study is located in the top 20 cm (Moraes et al. 1995). The values for the soils sampled at the benchmark sites in Brazil are exceptionally low when compared with the range reported by Moraes et al. (1995) for undisturbed forests in the Amazon.

The soil carbon stocks for the other land use systems did not reflect the expected trends, with some land use systems having higher topsoil carbon than the forest systems (table 2.3). Generally, land use systems on soils with higher clay content had higher soil carbon, indicating that attempts at selecting land use systems on soils of similar texture within a chronosequence were unsuccessful. The wide range in soil carbon losses results from variation in the length of time since clearing, the type of land use, the soil type, and topsoil erosion. To correct for the differences in soil texture, the C_{rel} values of the different land use systems were used to indicate relative changes in soil carbon (table 2.3).

Table 2.3 Actual Soil Carbon Values and Values Corrected According to Soil Texture (equation 1, van Noordwijk et al. 1997a) and Soil Sampling Depth (van Noordwijk et al. 2000) and the Soil Carbon Stocks Measured for the Forest Systems and Corrected for the Land Use Systems Sampled at ASB Sites

Country and Land Use (sampling depth, cm)	C_{actual} (g/kg)	$C_{land\ use}/C_{forest}$ (uncorrected)	$C_{reference}$ (g/kg)	$C_{relative} = C_{actual}/C_{reference}$	Average Soil Carbon Stock,[a,b] t C/ha (*SD*)
Brazil (0–20)					
Forest	1.78	1.00	1.82	0.98	35 (1.3)
Agroforestry	1.52	0.85	1.91	0.80	28[c]
Fallow	0.96	0.54	1.52	0.63	22[c]
Pasture	1.12	0.63	1.54	0.73	26[c]
Crop	1.70	0.96	1.95	0.87	30[c]
Cameroon (0–20)					
Forest	1.56	1.00	1.62	0.97	45 (8.5)
Jungle cacao	1.47	0.94	1.43	1.03	46[c]
Fallow (8 yr)	1.72	1.10	1.65	1.04	47[c]
Fallow (2 yr)	1.49	0.96	2.30	0.65	39[c]
Crop	1.62	1.04	1.53	1.06	48[c]
Indonesia (0–5)					
Forest	1.01	1.00	1.00	1.01	48 (7.6)
Logged forest	1.21	1.20	1.09	1.11	49 (3.8)
Jungle rubber	1.91	1.89	1.59	1.20	54[c]
Pulpwood plantation	1.12	1.11	1.11	1.01	49[c]
Rubber plantation	1.54	1.52	1.90	0.81	39[c]
Cassava	1.09	1.08	1.64	0.66	32[c]
Imperata	0.76	0.75	1.59	0.48	23[c]

[a]Values for the forest systems are the measured values of soil carbon stocks of forest systems at the different ASB sites.

[b]Calculated as the forest soil carbon stock × $C_{reference}$.

[c]Indicates estimated time-averaged carbon for the topsoil.

The C_{rel} values for the forest systems in Brazil, Cameroon, and Indonesia were remarkably close to 1.0 (table 2.3), indicating that the equation for normalizing soil carbon for texture and sampling depth that was developed from soils in Indonesia applies well to other humid tropical forest sites. The C_{rel} index shows there was little or no change in soil carbon for most the land use systems considered in Cameroon, except for the 2-year fallows, which had 35 percent less soil carbon (table 2.3). This drop is indicative of the changes that occur the first 2 to 5 years after forest or fallow clearing, followed by a recovery of soil carbon as the fallow period increases. The lack of change in topsoil carbon in the other systems is consistent with the low land use intensity of this benchmark area. In contrast to Cameroon, topsoil carbon losses of 11 to 53 percent were found in the more intensive pastures and croplands in Brazil and degraded grasslands and continuous cropping in Indonesia. In general, the tree-based plantations and agroforestry systems lost less than 20 percent of the topsoil carbon, and the complex rubber and cacao agroforests had levels of soil carbon similar to the forests.

The relative soil carbon losses as calculated for the different land use systems are similar to those reported by Detwiler (1986) in a review of soil carbon changes with land use change in the humid tropics. Improved pasture management from the ASB sites in Brazil did not show an increase in the topsoil carbon compared with the traditional or degraded pastures, at least to levels that would be significant for carbon sequestration. Fisher et al. (1994) found substantial amounts of carbon in the roots and subsoil of improved pastures in the drier, subhumid savanna areas of Brazil. Subsoil carbon and roots were not measured in the ASB plots, so there may actually be some storage through improved pastures, although Nepstad et al. (1994) and Trumbore et al. (1995) found dramatic decreases in occurrence of deep roots on conversion of forest to pasture in the seasonal zone of the eastern Brazilian Amazon. Sommer et al. (2000) found that the biomass of deep roots and root patterns with depth were similar under forests and young secondary vegetation but substantially less under intensive plantations. These differences in root profiles were accompanied by decreases of 25 to 50 percent carbon in the topsoil in the plantations and a reduction in carbon throughout the profile. These findings indicate that there are also large losses of soil carbon at depth with the conversion of forest to other systems without deep rooting. More root and subsoil carbon measurements are needed on a variety of land use systems in different soil and climate regimes in the tropics to verify these findings.

Modeling Changes in Carbon Stocks with Changes in Land Use

CENTURY model simulations of the *Paraserianthes* pulpwood plantations and cassava–*Imperata* systems in Indonesia agreed with the vegetation carbon stocks measured in the field for the tree plantation and the cassava–*Imperata* systems (figure 2.2) (Sitompul et al. 1996). However, the biomass carbon simulated for the primary

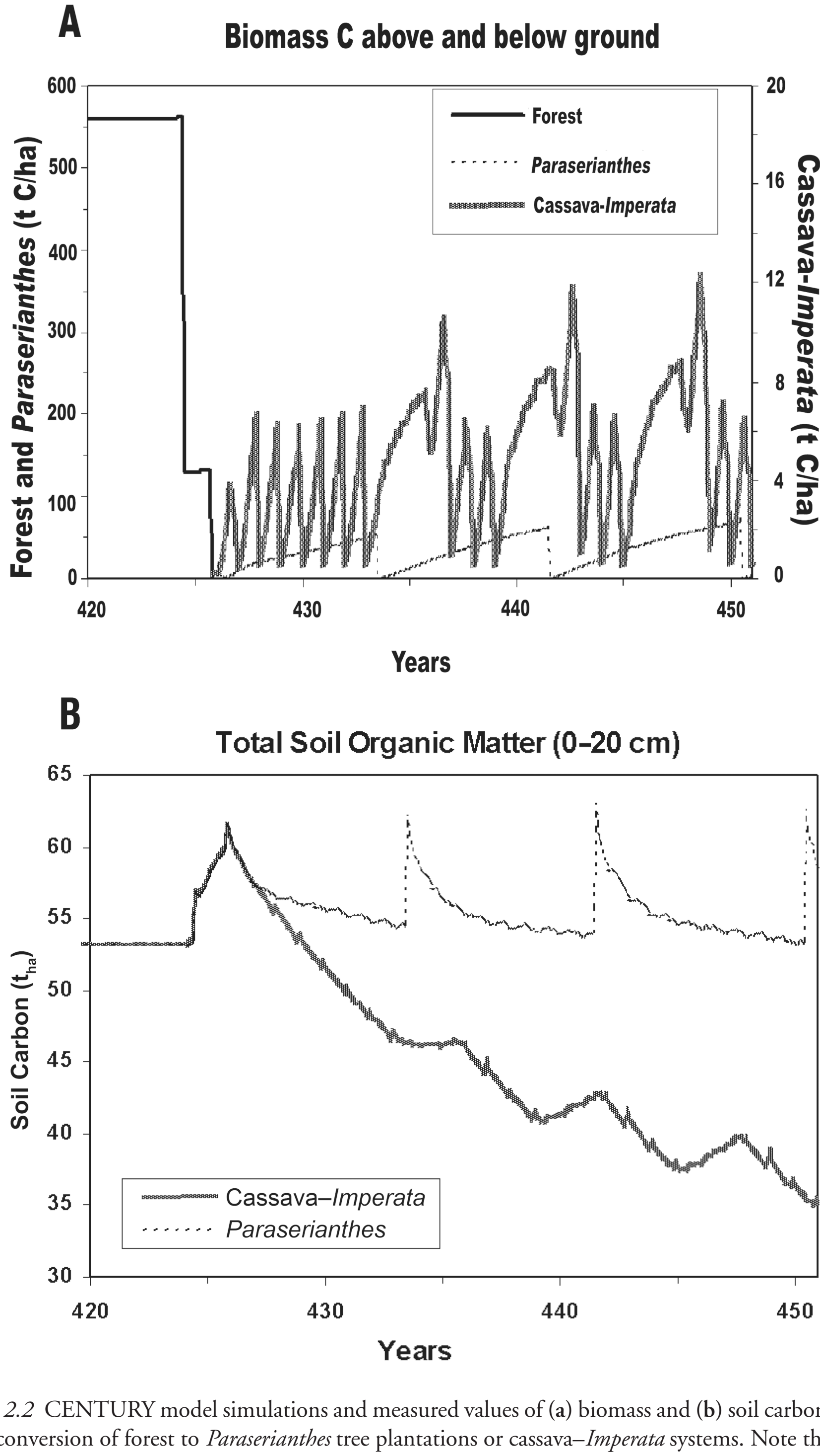


Figure 2.2 CENTURY model simulations and measured values of (**a**) biomass and (**b**) soil carbon changes on conversion of forest to *Paraserianthes* tree plantations or cassava–*Imperata* systems. Note the different *y*-axes for estimating carbon values in *Paraserianthes* and *Imperata* systems (Sitompul et al. 1996).

forest is high by about 25 percent, indicating there may be a need for further model parameterization and validation for the Indonesia site. The simulated topsoil soil carbon (figure 2.2) shows that the tree plantation maintains a steady-state level similar to that of the forest; the blips are a result of the slash that is added and decomposes after tree harvest. Field measurements also indicate little or no drop in soil carbon in the plantations (table 2.3). However, the cassava–*Imperata* simulation shows a dramatic and continuing decline in soil carbon, declining by 40 percent in 20 years, similar to that from field measurements.

The simulations reported for Cameroon of the current traditional slash-and-burn agriculture with a declining fallow phase and two alternative systems indicated a slight overestimation of total system carbon (Woomer et al. 2000). The model simulated 350 t C/ha in the undisturbed forest, compared with a measured total system carbon of 280 t C/ha for logged forests and 270 t/ha system carbon for a 20-year fallow compared with 210 t C/ha measured in those systems. Use of the model to simulate traditional slash-and-burn agriculture and an alternative land use that included soil conservation and retention of some of the larger trees showed increases in carbon stocks compared with that of the traditional system, but the system carbon still declined with decreasing fallow length but at a slower rate. These comparisons of measured and simulated changes in carbon stocks with several land use systems found in the humid tropics show that, with some minor adjustments, CENTURY Version 4.0 will be useful for extrapolating and predicting carbon changes for a variety of alternative land use systems.

CONCLUSION

Carbon losses and potential carbon sequestration associated with the various land use transitions can be estimated by combining information on the above-ground time-averaged carbon and the relative soil carbon values for the different land use systems (table 2.4, figure 2.3). In table 2.4 a net loss of carbon from the vegetation is considered a flux to the atmosphere and is indicated by a positive sign (+) with the values in the table. Likewise, a net sink of carbon into the vegetation is indicated by a negative sign (–).

The carbon losses from converting the natural forests to logged forests ranges from a low of 80, in the case of Cameroon, to a high of 200 t C/ha for Indonesia, assuming the carbon stock of the natural forests in all countries are similar to that of Indonesia. There is little if any carbon loss from the topsoil (table 2.3). Further losses from conversion of logged forests to other tree-based systems range from 40 to 190 t C/ha above ground and 6 to 12 t C/ha from the soil. Eventual conversion of logged forest to continuous cropping or pasture systems results in a net loss of 90 to 200 t C/ha from the vegetation and 12 to 27 t C/ha from the topsoil. It is important to note that these losses would be larger if roots were included in the calculations.

Table 2.4 Carbon Sequestered (–t C/ha) or Lost (+) from Above-Ground Vegetation by Converting from One Land Use System (column) to Another Land Use System (row)

Indonesia	**Primary Forest**	**Logged Forest**	**Jungle Rubber (permanent)**	**Jungle Rubber (rotational)**	**Oil Palm**	**Pulpwood Plantation**	**Crop–*Imperata***
Time-averaged C (t C/ha^{1})	**306**	**93**	**89**	**46**	**54**	**37**	**2**
Logged forest	213	NA	–4	–47	–39	–56	–91
Jungle rubber (permanent)	217	4	NA	–43	–35	–52	–87
Jungle rubber (rotation)	260	47	–43	NA	8	–9	–44
Oil palm	252	39	–35	–8	NA	–17	–52
Pulp plantation	269	56	–52	9	17	NA	–35
Crop–*Imperata*	304	91	–87	44	52	35	NA
Cameroon	**Logged Forest**	**Shifting Cultivation (long fallow)**	**Jungle Cacao (permanent)**	**Jungle Cacao (rotational)**	**Oil Palm**	**Crop–Bush Fallow**	**Crop–*Chromalaena* Fallow**
Time-averaged C (t C/ha^{1})	**228**	**77**	**89**	**61**	**36**	**38**	**6**
Forest	NA	–151	–139	–167	–192	–190	–222
Shifting cultivation	151	NA	12	–16	–41	–39	–71

Jungle cacao (permanent)	139	–12	NA	–28	–53	–51	–83
Jungle cacao (rotational)	167	16	28	NA	–25	–23	–55
Oil palm	192	41	53	25	NA	2	–30
Crop–bush fallow	190	39	51	23	–2	NA	–32
Crop–*Chromolaena*	222	71	83	55	30	32	NA
Brazil	**Logged Forest**	**Multistrata Agroforest**	**Coffee Plantation**	**Crop–Improved Fallow**	**Crop–Natural Fallow**	**Pasture**	
Time-averaged C (t C/ha^{1})	**148**	**61**	**11**	**11**	**7**	**3**	
Forest	NA	–87	–137	–137	–141	–145	
Multistrata agroforestry	87	NA	–50	–50	–54	–58	
Coffee	137	50	NA	0	–4	–8	
Crop–improved fallow	137	50	0	NA	–4	–4	
Crop–fallow	141	54	0	NA	NA	–8	
Pasture	145	58	8	8	4	NA	

Values are determined by subtracting the time-averaged carbon value for the system in the row from that of the time-averaged value of the system in the column (e.g., Indonesia, primary forest (306) to oil palm (54) = 306 – 54 = +252 t C lost to atmosphere).

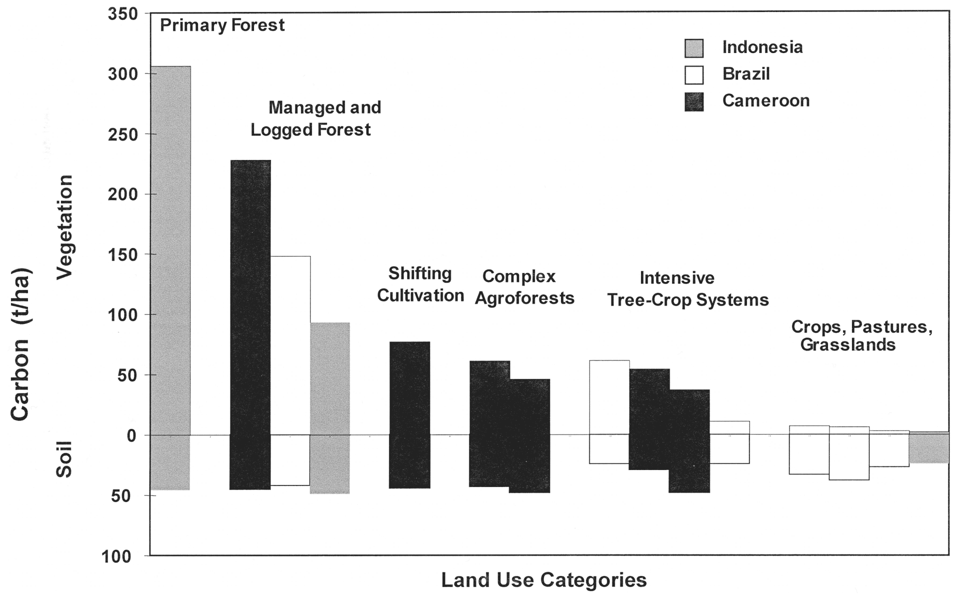


Figure 2.3 Above-ground time-averaged and topsoil (0–20 cm) carbon of the meta–land use systems for the three benchmark sites.

If croplands and pastures were taken as the endpoint, in terms of carbon stocks resulting from the conversion of tropical forests, then rehabilitation through conversion to tree-based systems would result in carbon sequestration. The amount of carbon that could be sequestered above ground would range from 5 t C/ha for coffee plantations to 60 t C/ha for more complex agroforestry systems over a 20- to 25-year period (table 2.4); 5 to 25 t C/ha could be sequestered in the topsoil (table 2.4). Silver et al. (2000) reported soil carbon sequestration rates of 1.3 t C/ha/yr for the first 20 years after reforestation or abandonment of agricultural lands or pastures in the tropics. Such rates would result in soil carbon sequestration values at the upper end of those estimated here for conversion of croplands to complex agroforestry systems over a 20-year time span. Overall our results indicate that the potential for carbon sequestration in the humid tropics is much greater above ground than in the topsoil, as was also shown by Sommer et al. (2000).

The total carbon sequestered through the establishment of tree-based systems depends on the areas of degraded grasslands, pastures, or croplands available for conversion. Estimates of such areas in the humid tropics range from 300 million to 1 billion ha (Grainger 1988; Houghton et al. 1993). In addition to the major environmental benefits that could be gained from converting degraded lands to tree-based systems, many of these systems also provide net profit to the individual farmers (see chapter 17, this volume). Yet these conversions are not occurring on a broad scale. Reason for farmers not choosing to rehabilitate these degraded lands systems could be lack of planting materials, lack of funds to purchase inputs, and the long lag between establishing the trees and realizing profits. Other obstacles include policy issues, such as land tenure and tree rights, and lack of infrastructure for input and output markets. The Clean Development Mechanism (CDM) of the Kyoto Protocol (UNFCCC 1997) may eventually provide a means of overcoming some of these obstacles. If land use change and forestry are eventually included under the CDM, this would allow industrialized nations to meet some of their greenhouse gas reductions via carbon offset projects that provide farmers with the inputs or policy changes needed to establish these profitable, tree-based systems that sequester carbon.

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